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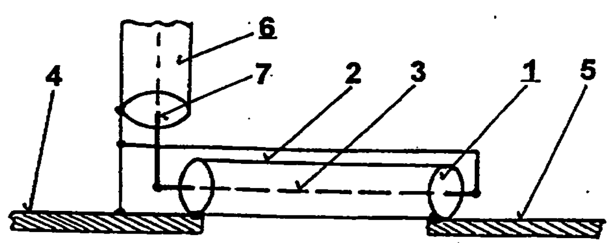
(56) Für die Beurteilung der Patentfähigkeit in Betracht gezogene Druckschriften:

KATSUTA, Ginzo et al.: Development of a New Detection Method of Partial Discharge for EHV Long-Distance Active Cable Line. In: Electrical Engineering in Japan, Vol. 112, No. 7, 1992, pp. 77-91;
KATSUTA, Ginzo et al.: Development of a method of Partial discharge detection in extra-high voltage cross-linked polyethylene insulated cable lines. in: IEEE Transactions on Power Delivery, Vol. 7, No. 3, July 1992, pp 1068-1075;
OGINO, M;
ICHIARA, M.;
FUJIMORI, A.: Recent Developments in Japan of Insulation Diagnostic Technology for Extra-High Voltage XLPE Cable Lines. In: CIGRE-Session, Paris, 28. Aug. - 3. Sept. 1994, 21 - 103, pp 2-9;

# (54) Anordnung zum Nachweis von Teilentladungen an Verbindungsstellen von Hochspannungskabeln

(57) Die Erfindung bezieht sich auf eine Anordnung zum Nachweis von Teilentladungen (TE) an Verbindungsstellen von Hochspannungskabeln, die Verbindungselemente besitzen, z. B. Muffen, mit denen Teilstücke von Hochspannungskabeln untereinander oder mit hochspannungstechnischen Einrichtungen verbunden sind. Es soll die Aufgabe gelöst werden, eine sichere Detektion des Entstehungsortes von TE, deren Unterscheidung zu Störimpulsen und eine hohe Empfindlichkeit zu erreichen. Erfindungsgemäß wird eine Breitband-Wellenübertrageranordnung vorgeschlagen, die spezielle Breitband-Wellenübertrager benutzt, deren jeweilige Primärleiter 2, die Außenleiter 4 des Hochspannungskabels mit der Abschirmung 5 der Muffe verbinden, während die Sekundärleiter 3 in besonderer Anschaltungsart mit einer Auswerteeinheit verbunden sind. Für die Breitband-Wellenübertrager wird eine bestimmte Impedanz gewählt, und sie sind mit ihren geometrischen Abmessungen an die Impulsdauern der möglichen TE-Impulse angepaßt und so geschaltet, daß gleichphasige TE-Impulse von der zu überwachenden Verbindungsstelle entstehen würden.

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Umfang des Kabels bzw. der Muffe symmetrisch anzuordnen. Dabei wird deren Anschaltung so vorgenommen, daß die TE-Impulse an den Ausgängen gleichphasig anliegen, wobei letztere parallelgeschaltet sind.

Mit dieser Anordnung ist es nunmehr möglich, eine wesentlich genauere Bestimmung des Zustandes der Isolationsfähigkeit, z. B. nach der Montage einer Hochspannungskabelmuffe oder beim Betrieb durchzuführen.

Die Erfindung soll nachstehend anhand eines Ausführungsbeispieles und einer Zeichnung näher erläutert werden.

In der Zeichnung zeigen:

**Fig.** 1 Schaltschema für Breitband-Wellenübertrager,

**Fig.** 2 Anordnungsprinzip für TE-Auskopplung,

**Fig.** 3/4 Impulsdiagramme für TE-Impulse.

In der **Fig.** 1 ist das Anschaltschema eines Breitband-Wellenübertragers in Verbindung mit einem Hochspannungskabel und einer Muffe gezeigt. Dieser Übertrager besteht aus einem, hier gestreckt gezeichneten Koaxialkabelstück **1**, dessen Mantel einen Primärleiter **2** und dessen Seele einen Sekundärleiter **3** bildet. Der Primärleiter **2** stellt die stromführende Verbindung zwischen einem Außenleiter **4** am Ende des nicht dargestellten Hochspannungskabels und einer leitfähigen Abschirmung **5**, der ebenfalls nicht dargestellten Muffe her. Von Bedeutung ist, daß das eine Ende des Sekundärleiters **3** an den Außenleiter **4** zurückgeführt und mit diesem galvanisch verbunden, das "kalte" Ende zum Anschluß für den neutralen Leiter des Zuleitungskabels **6** bildet, der zu einer in der **Fig.** 1 nicht gezeigten Auswerteeinheit führt. Das Zuleitungskabel **6** für diese ist ebenfalls wieder koaxial ausgeführt und es wurde eine bestimmte Impedanz gewählt. Diese hängt einerseits von den örtlichen Gegebenheiten und andererseits von der geforderten Empfindlichkeit ab. Die Seele **7** des Zuleitungskabels **6** ist mit dem anderen Ende des Sekundärleiters **3** verbunden. Die Auskopplung der TE-Impulse erfolgt nahezu originalgetreu, wenn die geometrische Länge vergleichbar mit der elektrischen Länge des TE-Impulses ist, die durch die Impulsdauer und die Wellengeschwindigkeit im Kabel bzw. der Muffe definiert ist. Wird beispielsweise eine Kabelmuffe mit einem Breitband-Wellensensor zusammengeschaltet, wobei die geometrische Länge der Muffe z. B. 2 m beträgt dann könnten bei Annahme einer Wellengeschwindigkeit von 16 cm/ns TE-Impulse mit einer Dauer von < 10 ns nahezu originalgetreu nachgewiesen werden. Diese Bedingung ist für reale Impulse, die in Hohlräumen von Feststoffisolierungen zünden, stets erfüllt.

Eine solche Anordnung ist als Prinzip in der **Fig.** 2 dargestellt. Hierbei sind rechts und links auf der Zeichnung die beiden Enden zweier Teilstücke **8; 9** eines Hochspannungskabels und in der Mittel eine verbindende Muffe **10** schematisch gezeigt. Ein Hochspannung führender Leiter **11** ist im Inneren gestrichelt dargestellt, der im Bereich der Teilstücke **8; 9** von den Außenleitern **4** allseitig umgeben wird. Die Isolation ist nicht gezeigt. Die Abschirmung **5** der Muffe **10** ist über je einem Breitband-Wellenübertrager **12; 13** mit dem jeweiligen Außenleiter **4** der Teilstücke **8; 9** verbunden, wobei auch mehrere Breitband-Wellenübertrager symmetrisch angeordnet werden können. Diese erfüllen neben der Erfassung der TE-Impulse im Nanosekunden-Zeitbereich gleichzeitig die Funktion des Überspannungsschutzes, z. B. bei möglichen Schaltüberspannungen. Zur Bewertung der TE werden diese von den Breitband-Wellenübertragern **12; 13** einer Auswerteeinheit **14** zugeführt, in der zunächst eine Impuls-Richtungsdiskrimination erfolgt und nach verschiedenen Umwandlungs- und Bewertungsprozessen eine genaue Aussage über Ort und Stärke der TE möglich ist.

In der **Fig.** 3 sind die über solche Breitband-Wellenübertrager erfaßten und ausgekoppelten Original-TE-Impulse mittels eines Hochleistungsoszilloskopes als Kurvenzüge festgehalten. Der Kurvenverlauf A entspricht dem Ausgangssignal am Breitband-Wellenübertrager **12**, der Kurvenverlauf B dem am Breitband-Wellenübertrager **13**. Es sind zwei überragende Impulsspitzen gleicher Polarität erkennbar, deren Beginn in Beziehung auf eine gemeinsame Zeitachse X eine Differenz aufweist. Durch Auswertung dieser Zeitdifferenz und Bezug auf eine Achse Y ist die genaue Stelle der TE innerhalb der Muffe bestimmbar.

Demgegenüber ist in **Fig.** 4 ersichtlich, daß bei vorher beschriebener entsprechender Anschaltung der Breitband-Wellenübertrager die Polaritäten der TE unterschiedlich sind, also die Entladungsstelle nicht im Muffenbereich, sondern in dem entsprechenden Teilstück des Hochspannungskabels liegt.

## Patentansprüche

1. Hochspannungskabeln, die Verbindungselemente besitzen, z. B. Endverschlüsse und Muffen (10), mit denen Hochspannungskabel bzw. Teilstücke davon, untereinander und/oder mit hochspannungstechnischen Einrichtungen verbunden sind, wobei das Verbindungselement eine eigene, den Innenleiter und seine Isolation hohlzylinderförmig umschließende leitfähige Abschirmung (5) besitzt, die mit dem Außenleiter (4) des Hochspannungskabels kontaktiert ist, **dadurch gekennzeichnet**, daß
   a) die Abschirmung (5) und der Außenleiter (4) über den Primärleiter (2) eines oder mehrerer Breitband-Wellenübertrager (12; 13) galvanisch verbunden sind,
   b) der Sekundärleiter (3) des Breitband-Wellenübertragers (12; 13) über ein Zuleitungskabel (6) mit einer Auswerteeinheit (14) in Verbindung steht, die einen Impulsrichtungsdiskriminator beinhaltet,
   c) die Leiterbahnen von Primärleiter (2) und Sekundärleiter (3) zumindest annähernd parallel geführt sind und ihre geometrische Länge in Abhängigkeit von der elektrischen Länge des TE Impulses dimensioniert ist,
   d) die Leiterbahn des Primärleiters (2) mit ihrem einen Ende am Außenleiter (4) und mit ihrem anderen Ende an der Abschirmung (5) galvanisch kontaktiert ist,
   e) die Leiterbahn des Sekundärleiters (3) mit dem Ende, das dem mit der Abschirmung (5) verbundenen Ende des Primärleiters (2) gegenüberliegt, an den gemeinsamen Verbindungspunkt von Außenleiter (4), Primärleiter (2) und Koaxialleiter des Zuleitungskabels (6) angeschlossen ist, während das andere Ende des Sekundärleiters (3), das dem gemeinsamen Verbindungspunkt von Außenleiter (4), Primärleiter (2) und Koaxialleiter des Zuleitungskabels (6) gegenüberliegt, mit der Seele (7) des Zuleitungskabels (6) verbunden ist.
2. Anordnung nach Anspruch 1, dadurch gekennzeichnet, daß die Muffe (10), die beide Teilstücke (8; 9) des Hochspannungskabels miteinander verbin-

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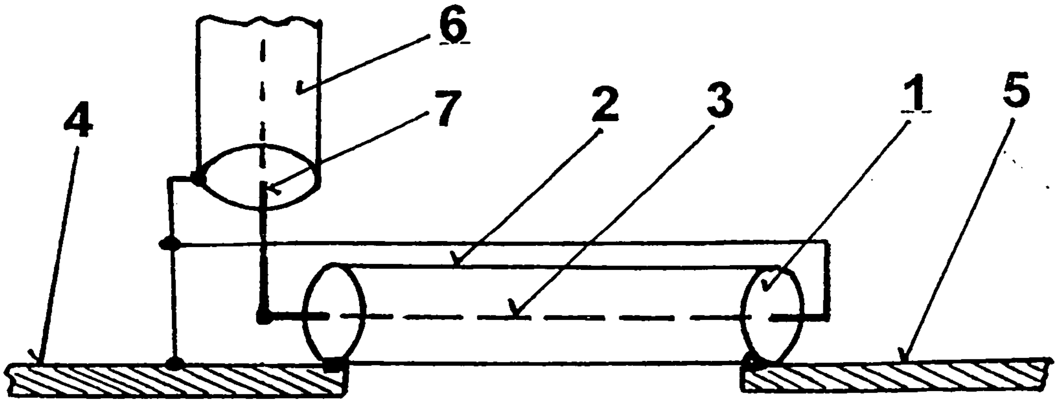


Fig. 1

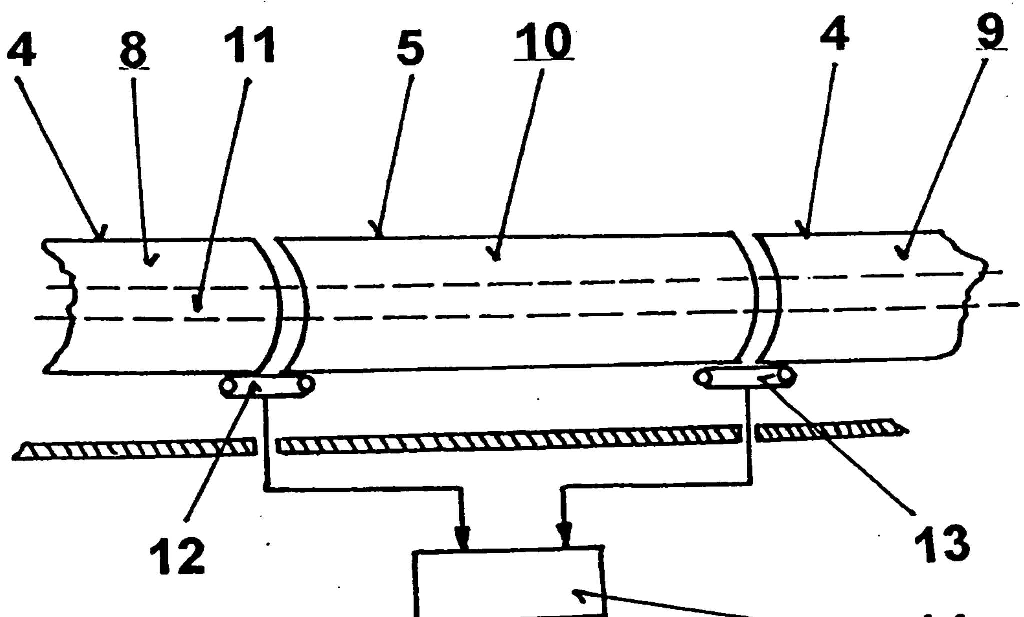


Fig. 2

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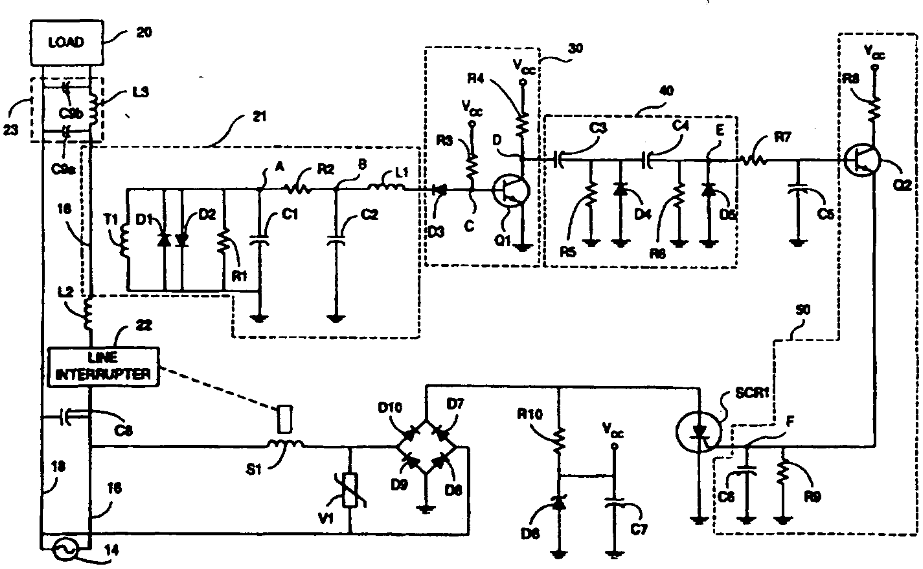



**(57) Abstract**

A system to detect arcing faults in an electrical distribution system with a line conductor connected to a utility power transformer. The system monitors the rate of change of electrical current in the line conductor and produces a signal which represents the rate of change. The system produces a pulse each time the rate-of-change signal exceeds a selected threshold, filters the rate-of-change signal and/or the pulses to substantially eliminate a signal or pulse which represents changes in the electrical current outside a selected frequency range, monitors the remaining pulses to detect when the number of pulses that occur within a selected time interval exceeds a predetermined threshold, and generates an arc-fault-detection signal in response to the occurrence of a number of pulses which exceed the threshold within the selected time interval.

# ARCING FAULT DETECTION SYSTEM

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of copending applications Serial No. 08/402,678, filed March 13, 1995 and entitled "DEVICE AND METHOD FOR BLOCKING SELECTED ARCING FAULT SIGNALS"; Serial No. 08/402,600, filed March 13, 1995 and entitled "VOLTAGE SENSING ARCING FAULT DETECTOR AND METHOD"; Serial No. 08/402,575, filed March 13, 1995 and entitled "ARCING FAULT DETECTION SYSTEM AND METHOD"; Serial No. 08/403,084, filed March 13, 1995 and entitled "DEVICE AND METHOD FOR TESTING ARCING FAULT DETECTORS"; and Serial No. 08/403,033, filed March 13, 1995 and entitled "CURRENT SENSING ARCING FAULT DETECTOR AND METHOD".

Each of the above applications has the same assignee as the present invention, and each is incorporated herein by reference in its entirety.

## FIELD OF THE INVENTION

The present invention relates to the protection of electric circuits and, more particularly, to the detection of hazardous arcing faults typically ignored by conventional circuit interrupters.

## BACKGROUND OF THE INVENTION

The electrical systems in residential, commercial and industrial applications usually include a panelboard for receiving electrical power from a utility source. The power is then routed through overcurrent protection devices to designated branch circuits supplying one or more loads. These overcurrent devices are typically circuit interrupters such as circuit breakers and fuses which are designed to interrupt the electrical current if the limits of the conductors supplying the loads are surpassed. Interruption of the circuit reduces the risk of injury or the potential of property damage from a resulting fire.

Circuit breakers are a preferred type of circuit interrupter because a resetting mechanism allows their reuse. Typically, circuit breakers interrupt an electric circuit due to a disconnect or trip condition such as a current overload or ground fault. The

Another object of the invention is to provide an arc fault detection system which can be conveniently retrofitted into existing residential, commercial and industrial facilities at minimal cost.

A further object of the invention is to provide an arc fault detection system and method which distinguishes between hazardous arc faults and normal operation of equipment or household appliances, as well as noisy loads, using the electrical circuit.

Still another object of the invention is to provide an arc fault detection system which electrically isolates multiple branch circuits in an electrical distribution system.

Other and further objects and advantages of the invention will be apparent to those skilled in the art from the present specification taken with the accompanying drawings and appended claims.

In accordance with the present invention, the foregoing objectives are realized by providing a system for detecting arcing faults in an electrical distribution system by monitoring the rate of change of electrical current in the line conductor and producing a signal representing the rate of change, producing a pulse each time the rate-of-change signal exceeds a selected threshold, filtering the rate-of-change signal and/or the pulses to substantially eliminate a signal or pulse representing changes in the electrical current outside a selected frequency range, monitoring the remaining pulses to detect when the number of pulses that occur within a selected time interval exceeds a predetermined threshold, and generating an arc-fault-detection signal in response to the occurrence of a number of pulses exceeding the threshold within the selected time interval.

## BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

FIG. 1 is a block diagram of an arc fault detection system embodying the present invention;

FIG. 2 is a schematic diagram of an electrical circuit for implementing the arc fault detection system illustrated in FIG. 1;

FIGs. 3a though 3g are waveforms at various points in the circuit of FIG. 2;

The pattern of fluctuations in the rate-of-change signal produced by the sensor 21 indicates whether the condition of the circuit is a normal load, a normal switching event, a phase-controlled fired load, or an arcing fault event. One example of a suitable sensor for producing the desired rate-of-change signal is a toroidal sensor having an annular core encompassing the current-carrying load line, with the sensing coil wound helically on the core. The core is made of magnetic material such as a ferrite, iron, or molded permeable powder capable of responding to rapid changes in flux. A preferred sensor uses a ferrite core wound with 200 turns of 24-36 gauge copper wire to form the sensing coil. An air gap may be cut into the core to reduce the permeability to about 30. The core material preferably does not saturate during the relatively high currents produced by parallel arcs, so that arc detection is still possible at those high current levels.

Other means for sensing the rate of change of the current in a line conductor are contemplated by the present invention. By Faraday's Law, any coil produces a voltage proportional to the rate of change in magnetic flux passing through the coil. The current associated with an arcing fault generates a magnetic flux around the conductor, and the coil of the sensor 21 intersects this flux to produce a signal. Other suitable sensors include a toroidal transformer with a core of magnetic material or an air core, an inductor or a transformer with a laminated core of magnetic material, and inductors mounted on printed circuit boards. Various configurations for the sensor core are contemplated by the present invention and include toroids which have air gaps in their body.

Preferably, the rate-of-change signal produced by the sensor 21 represents only fluctuations in the rate of change within a selected frequency band. The sensor bandpass characteristic is preferably such that the lower frequency cut-off point rejects the power frequency signals, while the upper frequency cut-off point rejects the high frequency signals generated in the presence of noisy loads such as a solder gun, electric saw, electric drill, or like appliances, equipment, or tools. The resulting output of the sensor 21 is thus limited to a selected frequency band associated with arcing faults, thereby eliminating or reducing spurious fluctuations in the rate-of-change signal which could result in nuisance tripping. As an example, the sensor bandpass characteristic may have: (1) a lower frequency cut-off point or

The operation of the circuit of FIG. 2 can be more clearly understood by reference to the series of waveforms in FIGs. 3a through 3g. FIG. 3a is an actual waveform from an oscilloscope connected to a line conductor 16 carrying a-c. power at 60 Hz and experiencing a high-frequency disturbance beginning at time t1. Because the high-frequency disturbance is within the frequency range to which the sensor 21 is sensitive (e.g., from about 10 KHz to about 100 KHz), the disturbance results in a burst of high-frequency noise in the di/dt output signal (FIG. 3b) from the sensor 21 (at point A in the circuit of FIG. 2), beginning at time t1. The noise burst has a relatively high amplitude from time t1 until approximately time t2, and then continues at a lower amplitude from time t2 to about time t3.

In the comparator 30, the magnitude of the rate-of-change signal from the sensor 21 is compared with the magnitude of a fixed reference signal, and the comparator 30 produces an output voltage only when the magnitude of the rate-of-change signal crosses that of the reference signal. This causes the detector 10 to ignore low-level signals generated by the sensor 21. All signals having a magnitude above the threshold level set by the magnitude of the reference signal are amplified to a preset maximum value to reduce the effect of a large signal. In the comparator 30, a transistor Q1 is normally turned on with its base pulled high by a resistor R3. A diode D3 changes the threshold and allows only the negative pulses from the sensor 21 to be delivered to the base of the transistor Q1. When the signal to the comparator drops below the threshold level (minus 0.2 volt for the circuit values listed below), this causes the transistor Q1 to turn off. This causes the collector of the transistor Q1 to rise to a predetermined voltage, determined by the supply voltage $V_{cc}$, a resistor R4 and the input impedance of a single-shot pulse generator circuit 40. This collector voltage is the output of the comparator circuit 30. The collector voltage remains high as long as the transistor Q1 is turned off, which continues until the signal from the sensor 21 rises above the threshold level again. The transistor Q1 then turns on again, causing the collector voltage to drop. The end result is a pulse output from the comparator, with the width of the pulse corresponding to the time interval during which the transistor Q1 is turned off, which in turn corresponds to the time interval during which the negative-going signal from the sensor 21 remains below the threshold level of the comparator.

The substantially uniform pulses produced by the circuit 40 are supplied to the base of a transistor Q2 through a current-limiting resistor R7. A capacitor C5 connected from the transistor base to ground improves the sharpness of the roll-off of the bandpass filtering. The transistor Q2 is the beginning of an integrator circuit 50 that integrates the pulses produced by the circuit 40. The pulses turn the transistor on and off to charge and discharge a capacitor C6 connected between the transistor emitter and ground. A resistor R9 is connected in parallel with the capacitor C6, and a resistor R8 connected between the supply voltage and the collector of the transistor Q2 determines the level of the charging current for the capacitor C6. The magnitude of the charge on the capacitor at any given instant represents the integral of the pulses received over a selected time interval. Because the pulses are substantially uniform in width and amplitude, the magnitude of the integral at any given instant is primarily a function of the number of pulses received within the selected time interval immediately preceding that instant. Consequently, the value of the integral can be used to determine whether an arcing fault has occurred.

The integral signal produced by the circuit 50 is shown in FIG. 3g, taken at point F in the circuit of FIG. 2. It can be seen that the integrator circuit charges each time it receives a pulse from the circuit 40, and then immediately begins to discharge. The charge accumulates only when the pulses appear at a rate sufficiently high that the charge produced by one pulse is less than the discharge that occurs before the next pulse arrives. If the pulses arrive in sufficient number and at a sufficient rate to increase the integral signal to a trip threshold level TR (FIG. 3g), SCR1 is triggered to trip the circuit breaker. The circuit is designed so that this occurs only in response to a di/dt signal representing an arc fault.

When SCR1 is turned on, a trip solenoid S1 is energized to disconnect the load from the circuit in the usual manner. Specifically, turning on SCR1 causes current to flow from line to neutral through a diode bridge formed by diodes D7-D10, thereby energizing the solenoid to open the circuit breaker contacts in the line 16 and thereby disconnect the protected portion of the system from the power source. The d-c. terminals of the diode bridge are connected across SCR1, and the voltage level is set by a zener diode D6 in series with a current-limiting resistor R10. A varistor V1 is connected across the diode bridge as a transient suppressor. A filtering

| | |
|---|---|
| C8 | 1.0uF |
| Q1 | 2N2222A |
| Q2 | 2N2222A |
| SCR1 | CR08AS-12 made by POWEREX-Equal |
| $V_{cc}$ | 27v |

Although a circuit breaker is the most commonly used line interrupter, the output device may be a comparator, SCR, relay, solenoid, circuit monitor, computer interface, lamp, audible alarm, etc.

It will be understood that a number of modifications may be made in the circuit of FIG. 2. For example, the discrete bandpass filter between the sensor and the comparator can be replaced with an active filter using an operational amplifier. As another example, a single-shot timer can be used in place of the single-shot pulse generator in the circuit of FIG. 2. This circuit can receive the output signal from an active filter as the trigger input to an integrated-circuit timer, with the output of the timer supplied through a resistor to the same integrator circuit formed by the resistor R9 and capacitor C6 in the circuit of FIG. 2.

FIG. 4 illustrates a frequency-to-voltage converter circuit that can be used in place of all the circuitry between point A and the integrator circuit in FIG. 2. In this circuit, the signal from point A in FIG. 2 is supplied through a resistor Ra to a frequency/voltage converter integrated circuit 55 such as an AD537 made by Analog Devices Inc. The output of the integrated circuit 55 is fed to a pair of comparators that form a conventional window comparator. Specifically, the output of the circuit 55 is applied to the inverting input of a comparator 56 and to the non-inverting input of a comparator 57. The other inputs of the comparators 56 and 57 receive two different reference signals A and B which set the limits of the window, i.e., the only signals that pass through the window comparator are those that are less than reference A and greater then reference B.

FIG. 5 illustrates an arc detector 10 for sensing the rate of change of the line voltage, i.e., dv/dt, rather than current. The sensor in this circuit is a capacitor C10 connected between a line conductor 16 and an inductor L10 leading to ground. The inductor L10 forms part of a bandpass filter that passes only those signals falling

interrupter 22 and the power source 14 to provide a low impedance path for an arcing fault from the load line 16 to the neutral line 18, independent of the impedance of the load 20. The capacitor C8 thus prevents a series path from being created between branch circuits, even though the power transformer 14 appears as a high impedance to the high frequency current that an arcing fault generates.

The isolating capacitor C8 allows the sensor 21 to be sensitive even when all the loads are off-line and the impedance is high. As the loads come on-line, the impedance decreases. Without the isolating capacitor C8, a series path could be created between branch circuits. For example, current flow along the neutral line of a first branch circuit, within which an arcing fault is generated, could travel along the load line of the first branch circuit. The current could then continue the load line of a second branch circuit, subsequently flowing along the neutral line of the second branch circuit. The isolating capacitor C8 prevents this pathway between branch circuits from being formed.

With the voltage-type sensor shown in FIG. 5, isolation is provided by an inductor L2 in the load line 16 for each branch circuit. Each inductor L2 is located between the line interrupter 22 and the sensor 21 to provide an impedance for the current produced by an arcing fault.

The isolating capacitors C8 and the isolating inductors L2 may be used simultaneously in their respective positions in the branch circuits. This combination can be particularly useful if the sensors monitor both the current and voltage changes in the branch circuits to detect arcing faults. The arcing fault detection system also includes a blocking filter 23 in each branch circuit for blocking false arcing fault signals or other nuisance output signals generated by normal operation of the load 20. Each blocking filter 23 is connected between the sensor 21 and the load 20 in each branch circuit to prevent false arcing fault signals from being delivered to the sensor 21. As seen in FIGs. 2 and 5, the preferred blocking filter includes a pair of capacitors C9a and C9b connected between the load line 16 and the neutral line 18 of each branch circuit. An inductor L3 is connected in the load line 16 between the two capacitors C9a and C9b. Preferably, the capacitors C9a and C9b have a rating across the line of about 0.47 uF. The inductor L3 has a rating for 15 amps at 500 uH and dimensions of about 1.5" diameter and 1.313" in length (e.g., Dale IHV 15-

power conductors. If the fault level exceeds the trip level of the GFCI, which is usually at about 6 mA, the GFCI disconnects the circuit.

Three types of GFCI are commonly available. The first or separately enclosed type is available for 120-volt, 2-wire and 12/240-volt, 3-wire circuits up to 30 amp. The second type combines a 15-, 20-, 25-, or 30-amp circuit breaker and a GFCI in the same plastic case. It is installed in place of an ordinary breaker in a panelboard and is usually available in 120-volt, 2-wire, or 120/240-volt, 3-wire types which may also be used to protect a 240-volt, 2-wire circuit. The second type provides protection against ground faults and overloads for all outlets on the circuit. A third type having a receptacle and a GFCI in the same housing provides only ground-fault protection to the equipment plugged into that receptacle. There are feed-through types of GFCI which provide protection to equipment plugged into other ordinary receptacles installed downstream on the same circuit.

Ground fault equipment is commercially available from the Square D Company under the catalog designations GROUND CENSOR™, HOMELINE®, QO®, TRILLIANT® and MICROLOGIC® ground fault modules. This ground fault equipment is suitable for protection of main, feeder, and motor circuits on electrical distribution systems. It is also usable as ground fault relay and ground fault sensing devices. The arc detection systems described above can be advantageously used to supplement the circuit protection provided by all the foregoing types of GFCIs.

The term arcing fault, as used herein, includes faults caused by either series arcs (both line and neutral) or parallel arcs (line to line, line to ground, or line to neutral). The term arc, as used herein, includes not only a discharge of electricity through a gas or across an insulating medium, but also high impedance faults or other intended or unintended circuit paths which do not have sufficient energy or current flow to trip a breaker, but nevertheless can generate damaging heat or other undesirable effects.

The term mutual inductance, as used herein, is the property shared by neighboring inductors or inductive devices which enables electromagnetic induction to take place. The term rate of current or voltage change, as used herein, measures the change in the current or voltage over the period in time corresponding to the

**Claims:**

1. A method of detecting arcing faults in an electrical distribution system that includes a line conductor connected to a utility power transformer, said method comprising:

monitoring the rate of change of electrical current in the line conductor and producing a signal representing the rate of change,

producing a pulse each time the rate-of-change signal exceeds a selected threshold,

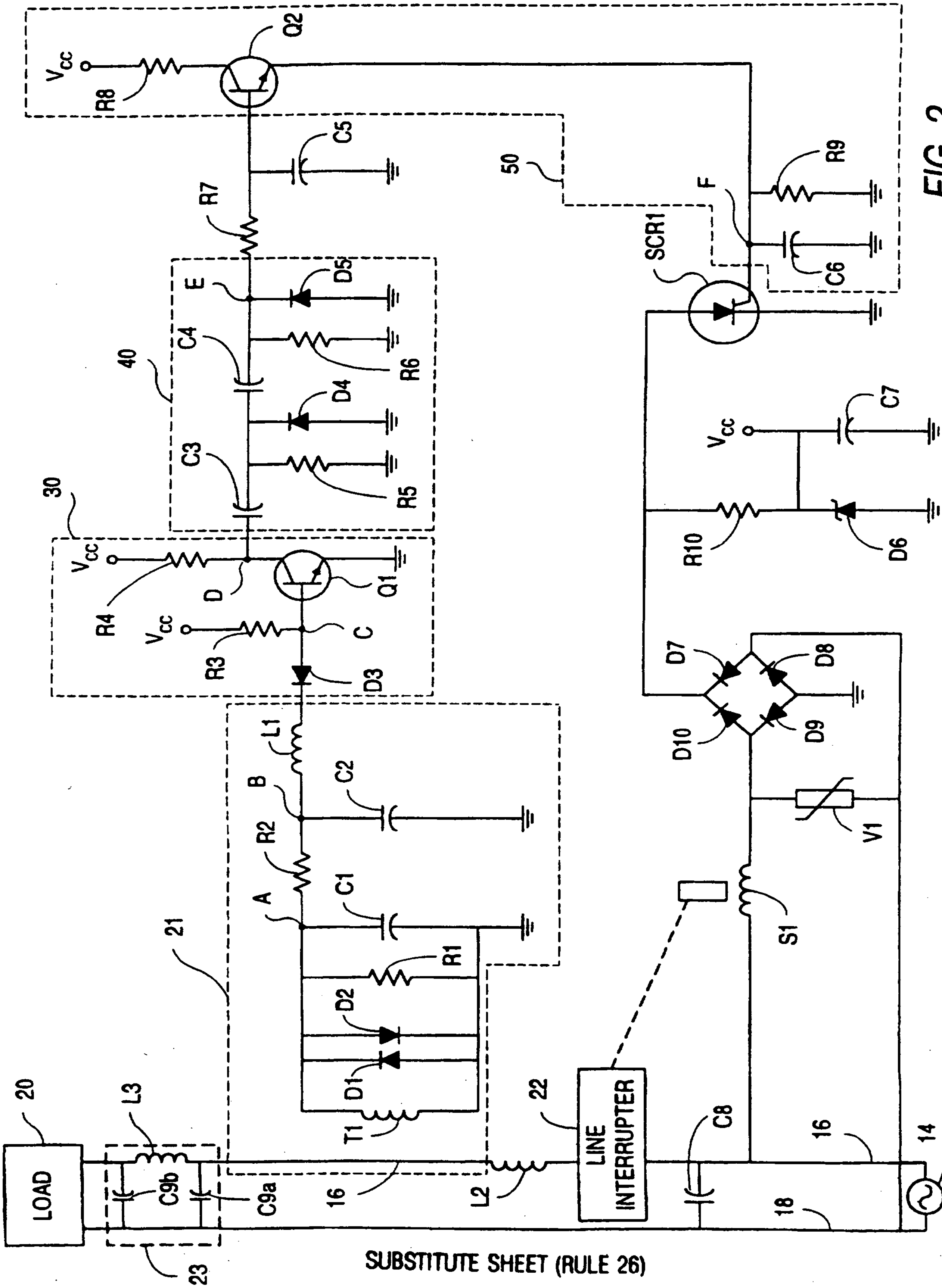
filtering at least one of said rate-of-change signal and said pulses to substantially eliminate a signal or pulse representing changes in said electrical current outside a selected frequency range,

counting the number of remaining pulses that occur within a selected time interval following each such pulse, and

generating an arc-fault-detection signal in response to the counting of a number of said remaining pulses exceeding a selected number within said selected time interval.

2. The method of claim 1 wherein said step of producing a pulse each time the rate-of-change signal exceeds a selected threshold includes a comparison of the amplitude of the rate-of-change signal to a predetermined reference signal.

3. The method of claim 1 wherein said filtering step comprises filtering said rate-of-change signal to substantially eliminate signals representing a rate of change outside the range from about 60Hz to about 1MHz.



Vcc
R8
Q2
C5
R7
50
R9
F
SCR1
C6
E
D5
C4
R6
40
D4
C3
R5
30
Vcc
R4
D
Q1
Vcc
R3
C
D3
C7
Vcc
R10
D6
D7
D8
D10
D9
L1
B
C2
R2
A
C1
R1
D2
D1
T1
V1
S1
21
20
L3
LOAD
C9b
C9a
23
16
L2
22
LINE INTERRUPTER
C8
16
18
14


FIG. 2

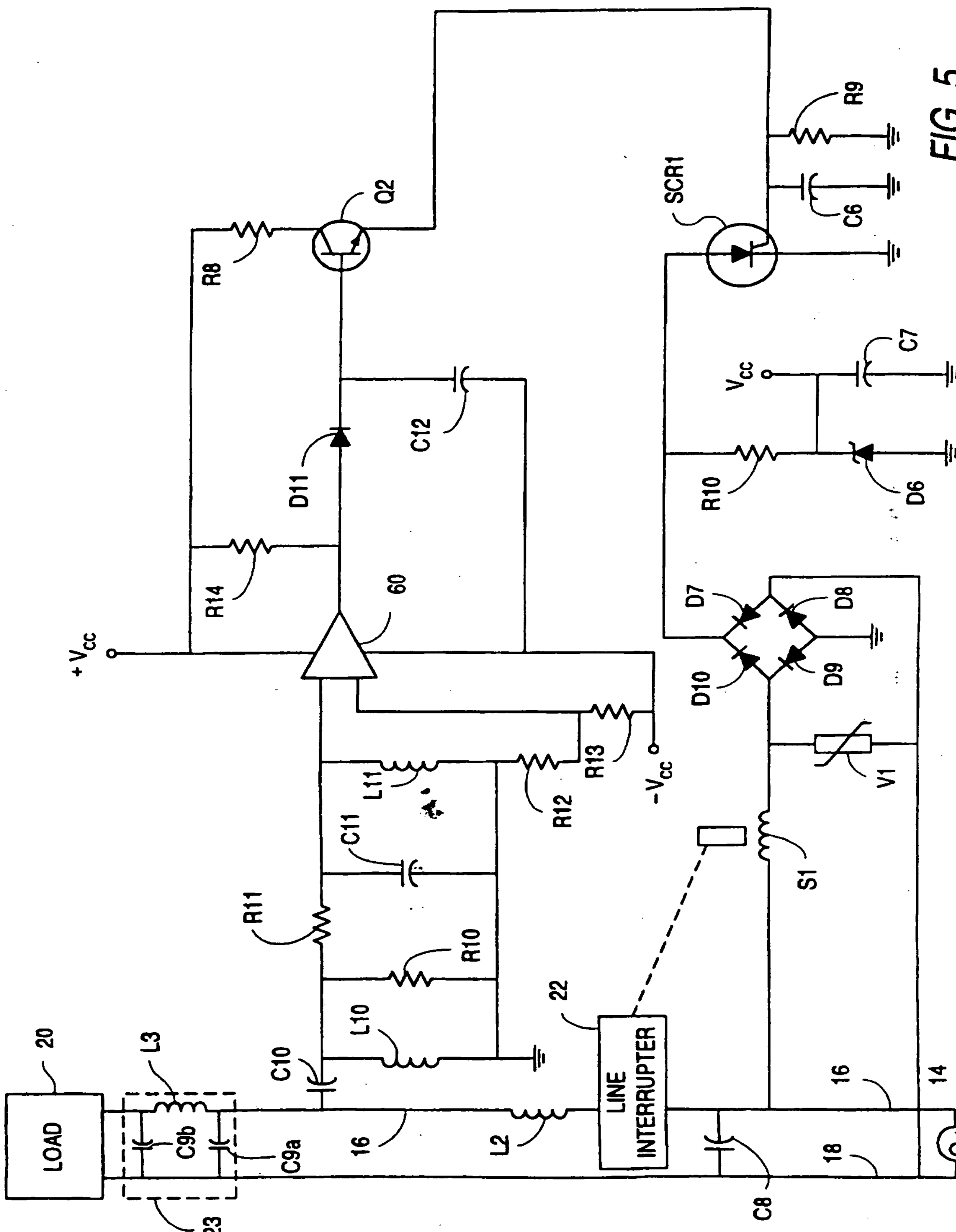



FIG. 5

SUBSTITUTE SHEET (RULE 26)

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 97/01869

| Patent document cited in search report | Publication date | Patent family member(s) | Publication date |
|---|---|---|---|
| EP 0615327 A | 14-09-94 | AU 676869 B | 27-03-97 |
| | | AU 5514794 A | 01-09-94 |
| | | CA 2116496 A | 27-08-94 |
| | | JP 6260075 A | 16-09-94 |
| | | ZA 9401138 A | 29-08-94 |

**CORRECTED VERSION***

# PCT

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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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| (51) International Patent Classification 6 : H02H 1/00 | A1 | (11) International Publication Number: **WO 97/30501**<br>(43) International Publication Date: 21 August 1997 (21.08.97) |

(21) International Application Number: PCT/US97/01869

(22) International Filing Date: 31 January 1997 (31.01.97)

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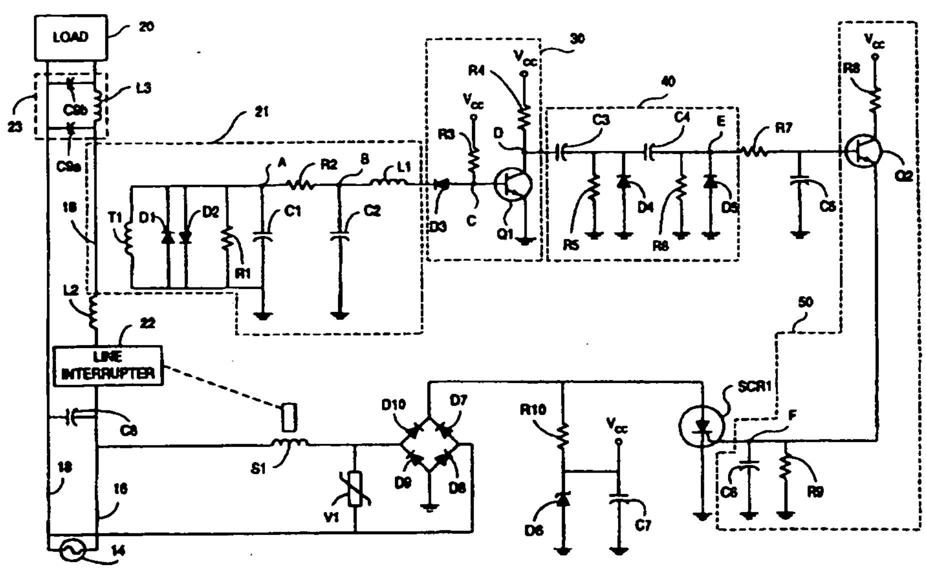
(74) Agent: GOLDEN, Larry, I.; Square D Company, 1415 South Roselle Road, Palatine, IL 60067 (US).

(54) Title: ARCING FAULT DETECTION SYSTEM




## (57) Abstract

A system to detect arcing faults in an electrical distribution system with a line conductor connected to a utility power transformer. The system monitors the rate of change of electrical current in the line conductor and produces a signal which represents the rate of change. The system produces a pulse each time the rate-of-change signal exceeds a selected threshold, filters the rate-of-change signal and/or the pulses to substantially eliminate a signal or pulse which represents changes in the electrical current outside a selected frequency range, monitors the remaining pulses to detect when the number of pulses that occur within a selected time interval exceeds a predetermined threshold, and generates an arc-fault-detection signal in response to the occurrence of a number of pulses which exceed the threshold within the selected time interval.

* (Referred to in PCT Gazette No. 10/1998, Section II)

# ARCING FAULT DETECTION SYSTEM

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of copending applications Serial No. 08/402,678, filed March 13, 1995 and entitled "DEVICE AND METHOD FOR BLOCKING SELECTED ARCING FAULT SIGNALS"; Serial No. 08/402,600, filed March 13, 1995 and entitled "VOLTAGE SENSING ARCING FAULT DETECTOR AND METHOD"; Serial No. 08/402,575, filed March 13, 1995 and entitled "ARCING FAULT DETECTION SYSTEM AND METHOD"; Serial No. 08/403,084, filed March 13, 1995 and entitled "DEVICE AND METHOD FOR TESTING ARCING FAULT DETECTORS"; and Serial No. 08/403,033, filed March 13, 1995 and entitled "CURRENT SENSING ARCING FAULT DETECTOR AND METHOD".

Each of the above applications has the same assignee as the present invention, and each is incorporated herein by reference in its entirety.

## FIELD OF THE INVENTION

The present invention relates to the protection of electric circuits and, more particularly, to the detection of hazardous arcing faults typically ignored by conventional circuit interrupters.

## BACKGROUND OF THE INVENTION

The electrical systems in residential, commercial and industrial applications usually include a panelboard for receiving electrical power from a utility source. The power is then routed through overcurrent protection devices to designated branch circuits supplying one or more loads. These overcurrent devices are typically circuit interrupters such as circuit breakers and fuses which are designed to interrupt the electrical current if the limits of the conductors supplying the loads are surpassed. Interruption of the circuit reduces the risk of injury or the potential of property damage from a resulting fire.

Circuit breakers are a preferred type of circuit interrupter because a resetting mechanism allows their reuse. Typically, circuit breakers interrupt an electric circuit due to a disconnect or trip condition such as a current overload or ground fault. The

Another object of the invention is to provide an arc fault detection system which can be conveniently retrofitted into existing residential, commercial and industrial facilities at minimal cost.

A further object of the invention is to provide an arc fault detection system and method which distinguishes between hazardous arc faults and normal operation of equipment or household appliances, as well as noisy loads, using the electrical circuit.

Still another object of the invention is to provide an arc fault detection system which electrically isolates multiple branch circuits in an electrical distribution system.

Other and further objects and advantages of the invention will be apparent to those skilled in the art from the present specification taken with the accompanying drawings and appended claims.

In accordance with the present invention, the foregoing objectives are realized by providing a system for detecting arcing faults in an electrical distribution system by monitoring the rate of change of electrical current in the line conductor and producing a signal representing the rate of change, producing a pulse each time the rate-of-change signal exceeds a selected threshold, filtering the rate-of-change signal and/or the pulses to substantially eliminate a signal or pulse representing changes in the electrical current outside a selected frequency range, monitoring the remaining pulses to detect when the number of pulses that occur within a selected time interval exceeds a predetermined threshold, and generating an arc-fault-detection signal in response to the occurrence of a number of pulses exceeding the threshold within the selected time interval.

## BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

FIG. 1 is a block diagram of an arc fault detection system embodying the present invention;

FIG. 2 is a schematic diagram of an electrical circuit for implementing the arc fault detection system illustrated in FIG. 1;

FIGs. 3a though 3g are waveforms at various points in the circuit of FIG. 2;

The pattern of fluctuations in the rate-of-change signal produced by the sensor 21 indicates whether the condition of the circuit is a normal load, a normal switching event, a phase-controlled fired load, or an arcing fault event. One example of a suitable sensor for producing the desired rate-of-change signal is a toroidal sensor having an annular core encompassing the current-carrying load line, with the sensing coil wound helically on the core. The core is made of magnetic material such as a ferrite, iron, or molded permeable powder capable of responding to rapid changes in flux. A preferred sensor uses a ferrite core wound with 200 turns of 24-36 gauge copper wire to form the sensing coil. An air gap may be cut into the core to reduce the permeability to about 30. The core material preferably does not saturate during the relatively high currents produced by parallel arcs, so that arc detection is still possible at those high current levels.

Other means for sensing the rate of change of the current in a line conductor are contemplated by the present invention. By Faraday's Law, any coil produces a voltage proportional to the rate of change in magnetic flux passing through the coil. The current associated with an arcing fault generates a magnetic flux around the conductor, and the coil of the sensor 21 intersects this flux to produce a signal. Other suitable sensors include a toroidal transformer with a core of magnetic material or an air core, an inductor or a transformer with a laminated core of magnetic material, and inductors mounted on printed circuit boards. Various configurations for the sensor core are contemplated by the present invention and include toroids which have air gaps in their body.

Preferably, the rate-of-change signal produced by the sensor 21 represents only fluctuations in the rate of change within a selected frequency band. The sensor bandpass characteristic is preferably such that the lower frequency cut-off point rejects the power frequency signals, while the upper frequency cut-off point rejects the high frequency signals generated in the presence of noisy loads such as a solder gun, electric saw, electric drill, or like appliances, equipment, or tools. The resulting output of the sensor 21 is thus limited to a selected frequency band associated with arcing faults, thereby eliminating or reducing spurious fluctuations in the rate-of-change signal which could result in nuisance tripping. As an example, the sensor bandpass characteristic may have: (1) a lower frequency cut-off point or

The operation of the circuit of FIG. 2 can be more clearly understood by reference to the series of waveforms in FIGs. 3a through 3g. FIG. 3a is an actual waveform from an oscilloscope connected to a line conductor 16 carrying a-c. power at 60 Hz and experiencing a high-frequency disturbance beginning at time t1. Because the high-frequency disturbance is within the frequency range to which the sensor 21 is sensitive (e.g., from about 10 KHz to about 100 KHz), the disturbance results in a burst of high-frequency noise in the di/dt output signal (FIG. 3b) from the sensor 21 (at point A in the circuit of FIG. 2), beginning at time t1. The noise burst has a relatively high amplitude from time t1 until approximately time t2, and then continues at a lower amplitude from time t2 to about time t3.

In the comparator 30, the magnitude of the rate-of-change signal from the sensor 21 is compared with the magnitude of a fixed reference signal, and the comparator 30 produces an output voltage only when the magnitude of the rate-of-change signal crosses that of the reference signal. This causes the detector 10 to ignore low-level signals generated by the sensor 21. All signals having a magnitude above the threshold level set by the magnitude of the reference signal are amplified to a preset maximum value to reduce the effect of a large signal. In the comparator 30, a transistor Q1 is normally turned on with its base pulled high by a resistor R3. A diode D3 changes the threshold and allows only the negative pulses from the sensor 21 to be delivered to the base of the transistor Q1. When the signal to the comparator drops below the threshold level (minus 0.2 volt for the circuit values listed below), this causes the transistor Q1 to turn off. This causes the collector of the transistor Q1 to rise to a predetermined voltage, determined by the supply voltage $V_{cc}$, a resistor R4 and the input impedance of a single-shot pulse generator circuit 40. This collector voltage is the output of the comparator circuit 30. The collector voltage remains high as long as the transistor Q1 is turned off, which continues until the signal from the sensor 21 rises above the threshold level again. The transistor Q1 then turns on again, causing the collector voltage to drop. The end result is a pulse output from the comparator, with the width of the pulse corresponding to the time interval during which the transistor Q1 is turned off, which in turn corresponds to the time interval during which the negative-going signal from the sensor 21 remains below the threshold level of the comparator.

The substantially uniform pulses produced by the circuit 40 are supplied to the base of a transistor Q2 through a current-limiting resistor R7. A capacitor C5 connected from the transistor base to ground improves the sharpness of the roll-off of the bandpass filtering. The transistor Q2 is the beginning of an integrator circuit 50 that integrates the pulses produced by the circuit 40. The pulses turn the transistor on and off to charge and discharge a capacitor C6 connected between the transistor emitter and ground. A resistor R9 is connected in parallel with the capacitor C6, and a resistor R8 connected between the supply voltage and the collector of the transistor Q2 determines the level of the charging current for the capacitor C6. The magnitude of the charge on the capacitor at any given instant represents the integral of the pulses received over a selected time interval. Because the pulses are substantially uniform in width and amplitude, the magnitude of the integral at any given instant is primarily a function of the number of pulses received within the selected time interval immediately preceding that instant. Consequently, the value of the integral can be used to determine whether an arcing fault has occurred.

The integral signal produced by the circuit 50 is shown in FIG. 3g, taken at point F in the circuit of FIG. 2. It can be seen that the integrator circuit charges each time it receives a pulse from the circuit 40, and then immediately begins to discharge. The charge accumulates only when the pulses appear at a rate sufficiently high that the charge produced by one pulse is less than the discharge that occurs before the next pulse arrives. If the pulses arrive in sufficient number and at a sufficient rate to increase the integral signal to a trip threshold level TR (FIG. 3g), SCR1 is triggered to trip the circuit breaker. The circuit is designed so that this occurs only in response to a di/dt signal representing an arc fault.

When SCR1 is turned on, a trip solenoid S1 is energized to disconnect the load from the circuit in the usual manner. Specifically, turning on SCR1 causes current to flow from line to neutral through a diode bridge formed by diodes D7-D10, thereby energizing the solenoid to open the circuit breaker contacts in the line 16 and thereby disconnect the protected portion of the system from the power source. The d-c. terminals of the diode bridge are connected across SCR1, and the voltage level is set by a zener diode D6 in series with a current-limiting resistor R10. A varistor V1 is connected across the diode bridge as a transient suppressor. A filtering

| | |
|---|---|
| C8 | 1.0uF |
| Q1 | 2N2222A |
| Q2 | 2N2222A |
| SCR1 | CR08AS-12 made by POWEREX-Equal |
| $V_{cc}$ | 27v |

Although a circuit breaker is the most commonly used line interrupter, the output device may be a comparator, SCR, relay, solenoid, circuit monitor, computer interface, lamp, audible alarm, etc.

It will be understood that a number of modifications may be made in the circuit of FIG. 2. For example, the discrete bandpass filter between the sensor and the comparator can be replaced with an active filter using an operational amplifier. As another example, a single-shot timer can be used in place of the single-shot pulse generator in the circuit of FIG. 2. This circuit can receive the output signal from an active filter as the trigger input to an integrated-circuit timer, with the output of the timer supplied through a resistor to the same integrator circuit formed by the resistor R9 and capacitor C6 in the circuit of FIG. 2.

FIG. 4 illustrates a frequency-to-voltage converter circuit that can be used in place of all the circuitry between point A and the integrator circuit in FIG. 2. In this circuit, the signal from point A in FIG. 2 is supplied through a resistor Ra to a frequency/voltage converter integrated circuit 55 such as an AD537 made by Analog Devices Inc. The output of the integrated circuit 55 is fed to a pair of comparators that form a conventional window comparator. Specifically, the output of the circuit 55 is applied to the inverting input of a comparator 56 and to the non-inverting input of a comparator 57. The other inputs of the comparators 56 and 57 receive two different reference signals A and B which set the limits of the window, i.e., the only signals that pass through the window comparator are those that are less than reference A and greater then reference B.

FIG. 5 illustrates an arc detector 10 for sensing the rate of change of the line voltage, i.e., dv/dt, rather than current. The sensor in this circuit is a capacitor C10 connected between a line conductor 16 and an inductor L10 leading to ground. The inductor L10 forms part of a bandpass filter that passes only those signals falling

interrupter 22 and the power source 14 to provide a low impedance path for an arcing fault from the load line 16 to the neutral line 18, independent of the impedance of the load 20. The capacitor C8 thus prevents a series path from being created between branch circuits, even though the power transformer 14 appears as a high impedance to the high frequency current that an arcing fault generates.

The isolating capacitor C8 allows the sensor 21 to be sensitive even when all the loads are off-line and the impedance is high. As the loads come on-line, the impedance decreases. Without the isolating capacitor C8, a series path could be created between branch circuits. For example, current flow along the neutral line of a first branch circuit, within which an arcing fault is generated, could travel along the load line of the first branch circuit. The current could then continue the load line of a second branch circuit, subsequently flowing along the neutral line of the second branch circuit. The isolating capacitor C8 prevents this pathway between branch circuits from being formed.

With the voltage-type sensor shown in FIG. 5, isolation is provided by an inductor L2 in the load line 16 for each branch circuit. Each inductor L2 is located between the line interrupter 22 and the sensor 21 to provide an impedance for the current produced by an arcing fault.

The isolating capacitors C8 and the isolating inductors L2 may be used simultaneously in their respective positions in the branch circuits. This combination can be particularly useful if the sensors monitor both the current and voltage changes in the branch circuits to detect arcing faults. The arcing fault detection system also includes a blocking filter 23 in each branch circuit for blocking false arcing fault signals or other nuisance output signals generated by normal operation of the load 20. Each blocking filter 23 is connected between the sensor 21 and the load 20 in each branch circuit to prevent false arcing fault signals from being delivered to the sensor 21. As seen in FIGs. 2 and 5, the preferred blocking filter includes a pair of capacitors C9a and C9b connected between the load line 16 and the neutral line 18 of each branch circuit. An inductor L3 is connected in the load line 16 between the two capacitors C9a and C9b. Preferably, the capacitors C9a and C9b have a rating across the line of about 0.47 uF. The inductor L3 has a rating for 15 amps at 500 uH and dimensions of about 1.5" diameter and 1.313" in length (e.g., Dale IHV 15-

power conductors. If the fault level exceeds the trip level of the GFCI, which is usually at about 6 mA, the GFCI disconnects the circuit.

Three types of GFCI are commonly available. The first or separately enclosed type is available for 120-volt, 2-wire and 12/240-volt, 3-wire circuits up to 30 amp. The second type combines a 15-, 20-, 25-, or 30-amp circuit breaker and a GFCI in the same plastic case. It is installed in place of an ordinary breaker in a panelboard and is usually available in 120-volt, 2-wire, or 120/240-volt, 3-wire types which may also be used to protect a 240-volt, 2-wire circuit. The second type provides protection against ground faults and overloads for all outlets on the circuit. A third type having a receptacle and a GFCI in the same housing provides only ground-fault protection to the equipment plugged into that receptacle. There are feed-through types of GFCI which provide protection to equipment plugged into other ordinary receptacles installed downstream on the same circuit.

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**Claims:**

1. A method of detecting arcing faults in an electrical distribution system that includes a line conductor connected to a utility power transformer, said method comprising:

monitoring the rate of change of electrical current in the line conductor and producing a signal representing the rate of change,

producing a pulse each time the rate-of-change signal exceeds a selected threshold,

filtering at least one of said rate-of-change signal and said pulses to substantially eliminate a signal or pulse representing changes in said electrical current outside a selected frequency range,

counting the number of remaining pulses that occur within a selected time interval following each such pulse, and

generating an arc-fault-detection signal in response to the counting of a number of said remaining pulses exceeding a selected number within said selected time interval.

2. The method of claim 1 wherein said step of producing a pulse each time the rate-of-change signal exceeds a selected threshold includes a comparison of the amplitude of the rate-of-change signal to a predetermined reference signal.

3. The method of claim 1 wherein said filtering step comprises filtering said rate-of-change signal to substantially eliminate signals representing a rate of change outside the range from about 60Hz to about 1MHz.

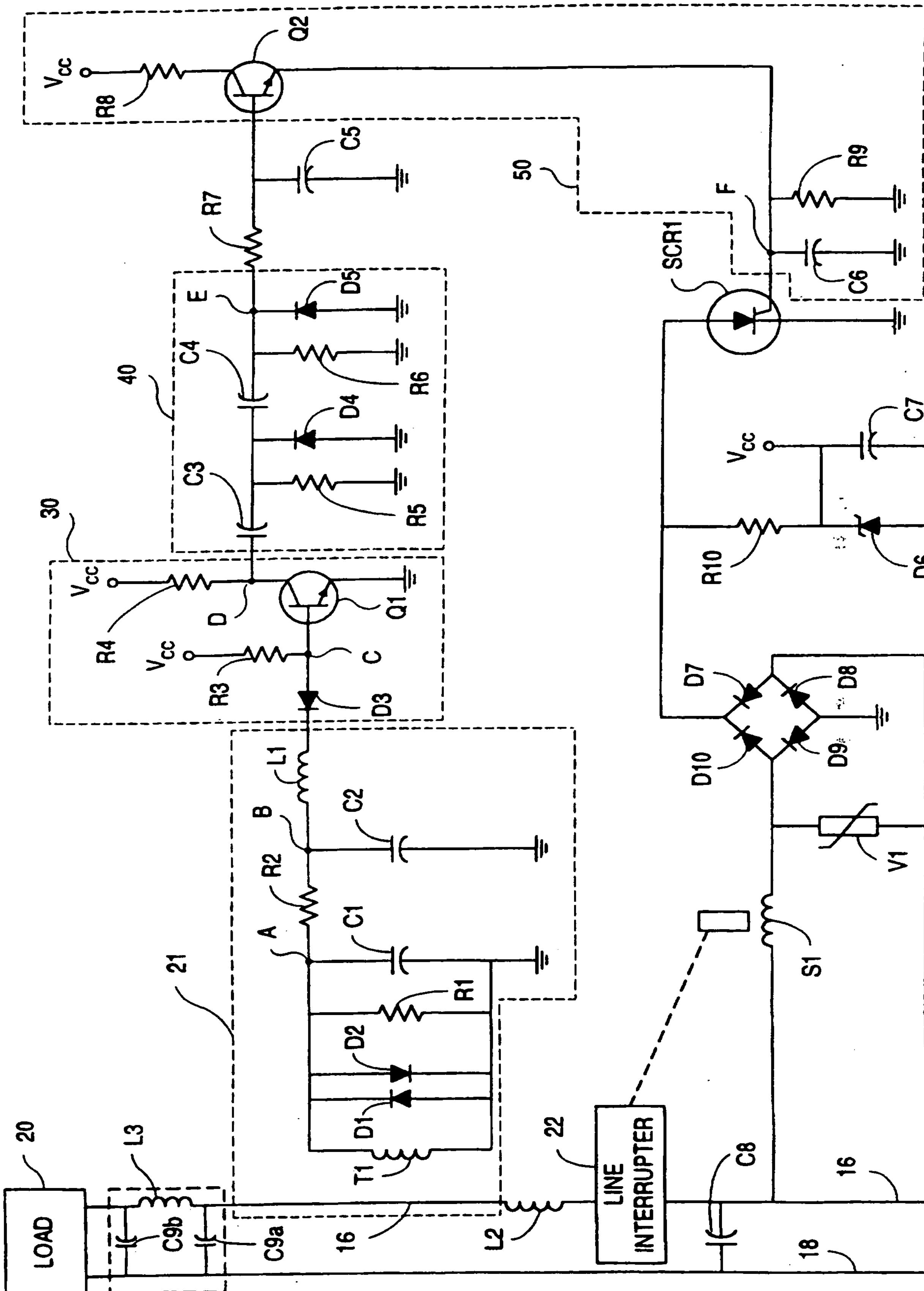


FIG. 2

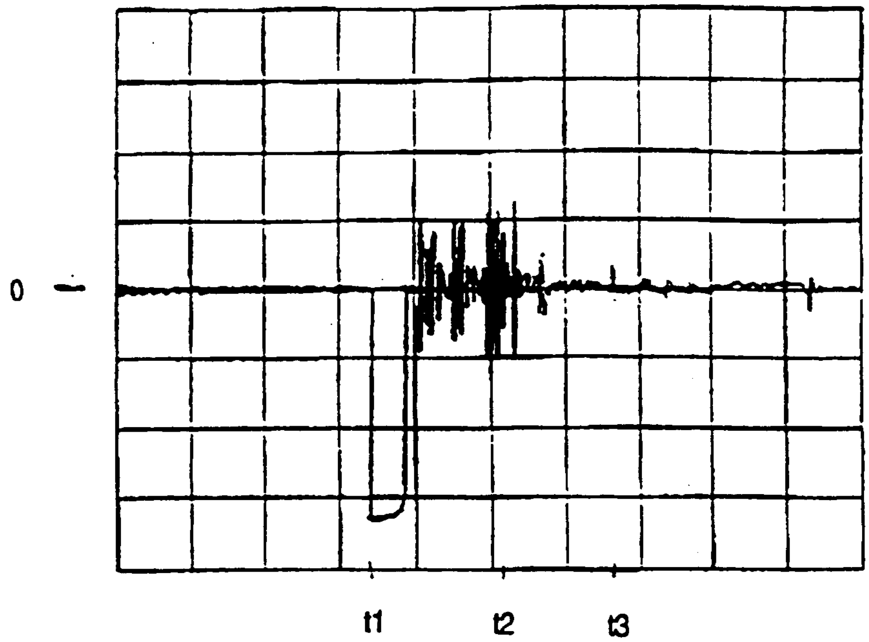


FIG. 3c

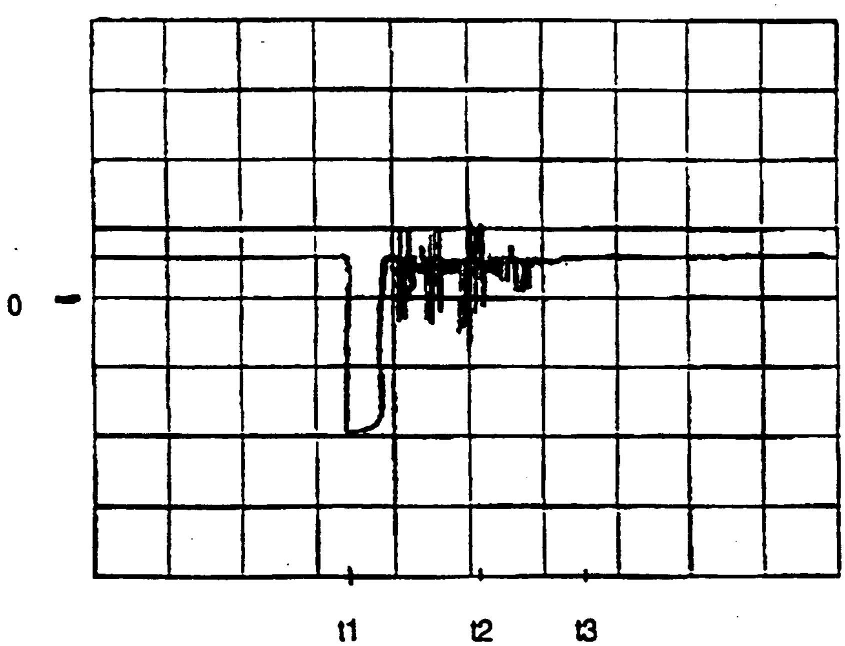


FIG. 3d

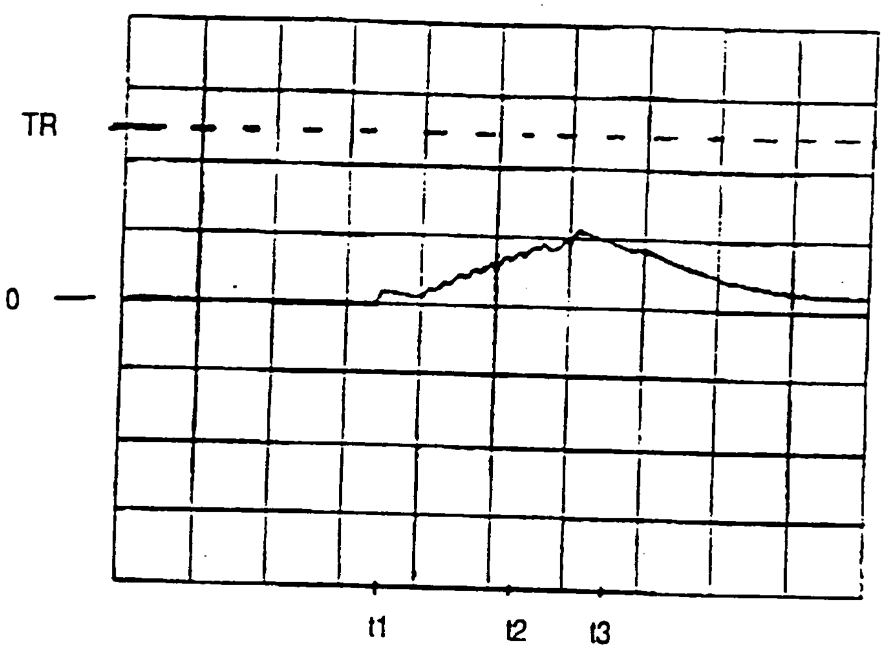


FIG. 3g

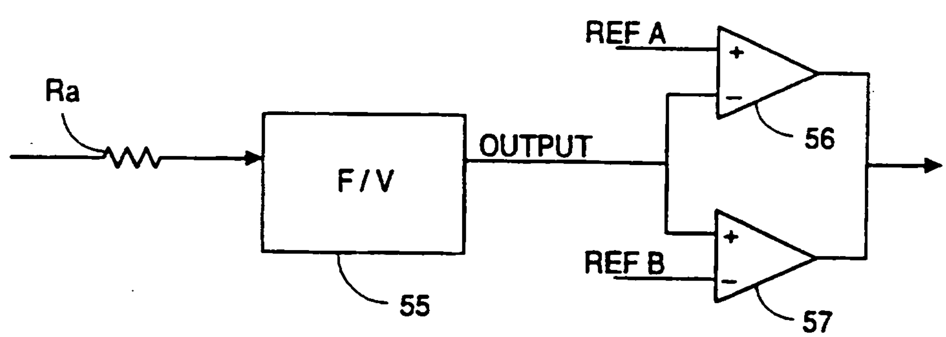


FIG. 4

# INTERNATIONAL SEARCH REPORT

Inte  nal Application No
PCT/US 97/01869

**A. CLASSIFICATION OF SUBJECT MATTER**
IPC 6 H02H1/00

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H02H H02B G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category ° | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X | EP 0 615 327 A (WESTINGHOUSE ELECTRIC CORP) 14 September 1994<br>see column 4, line 43 - column 6, line 25; figure 1<br>----- | 1-3 |

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

1

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 3 June 1997 | 13. 06. 97 |

| Name and mailing address of the ISA | Authorized officer |
|---|---|
| European Patent Office, P.B. 5818 Patentlaan 2<br>NL - 2280 HV Rijswijk<br>Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,<br>Fax: (+31-70) 340-3016 | Salm, R |